A Gate Compensated Gain Enhanced Transconductance Amplifier

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Abstract

The proposed work is about a gain-enhanced transconductance amplifier with improved phase margin and higher bandwidth. An amplifier is designed and evaluated for three main performance metrics namely gain or transconductance, phase margin and bandwidth. Miller compensation is performed on conventional OTA to improve phase margin while Gate compensation to improve its bandwidth as well. The proposed OTA is designed and implemented to improve gain of the amplifier as compared to conventional OTA. Differential amplifier pairs are replaced with telescopic amplifier pairs to achieve high gain. It is observed that implementation of telescopic topology approximately squares the gain of the conventional OTA. Bandwidth and phase margin remains the same as in conventional OTA. The simulation is done using the Spectre environment in the Cadence Virtuoso platform and under UMC 180nm Technology.

Keywords

Transconductance gain, Adaptive biasing, Miller compensation, Pole splitting, Gate compensation, Gain boosting, Telescopic Opamp.

1. **Introduction**

Operational transconductance amplifiers (OTAs) can be categorized as active circuits that amplify and produce a larger current at the output when a differential input voltage that is comparatively small is applied. Its main applications include a wide range of analog circuits such as filters, oscillators, and power amplifiers. Additionally, OTA's can be implemented in closed-loop control systems, eg., voltage-controlled oscillators, active filters and other such applications. Due to its properties like high input impedance and provide high voltage gain, they are useful in many other signal processing applications within the analog domain. OTAs are also mostly used in linear applications without negative feedback for open-loop configurations. This is due to the high resistance at the output node that decides the output voltage and can be selected to prevent the OTA from being in the saturation region, even with comparatively higher differential input voltages. Also , OTAs provide a large dc gain even for single stage opamp. Their high output impedance value makes them suitable for driving the capacitive loads found in CMOS integrated circuits. With feedback, they can also drive some resistive load [5]. OTA has high gain and the gain of OTA can be enhanced with the help of biasing current but this will lead to higher power consumption [2] . For many applications working at high frequency, specifically in filter applications, manual, automatic tuning is required to achieve precision. Gate voltage of M3 and M4 can be controlled by varying resistor R_G which is connected between drain and Source of M3 and M8 [4]. Miller compensation introduces pole splitting that moves one pole towards the origin and another one away from the origin. In the modified circuit , Miller compensation is performed by capacitor C_X and resistor R_X. The pole splitting is caused by Capacitor C_X . Hence two consecutive poles are separated from each other. This phenomena gives the improved phase margin but the bandwidth is now compromised . It also gives an extra right half plane (RHP) zero that will be adjusted by Series resistor (R_X) [6].

The second modified circuit has an R_G resistor Between gate and drain terminal of M3 and M4 PMOS. These MOSFETs are used for primary current mirror pairs [2]. This introduced a new Pole Zero Pair.The dominant pole gives the bandwidth of the system and by adjusting R_G the dominant pole effect is reduced to get improved bandwidth .

After study of these phenomena the Telescopic Topology is proposed instead of the Differential pair. Telescopic topology has high gain as compared to Differential pairs. In proposed Design M1 and M2 acts as input pair and M23-M28 mosfets used as gain enhancement stages.

For high gain, the transconductance of the circuit should be high. The conventional topologies available for gain enhancement are:

- Cascade
- Cascode
- Folded cascode
- Telescopic.

The Telescopic topology is implemented in this paper to improve the gain of the conventional OTA.

2. High Bandwidth Gate Compensated Transconductance Amplifier

Conventional OTA uses adaptive-biasing technique where N1 and N2 stages are used instead of MOSFETs used as a differential pair . N1 and N2 is formed with the fingering concept to get boosted currents i.e. I_B and I_B' and the overall biasing current I_B is also unaltered [2]. The first OTA has a very poor small phase margin. To improve this the Miller Compensation is used by introducing a Miller capacitor Cx and resistor R_X between differential pair output node i.e. node 1 and node 2 and the drain terminal of the second stage MOSFETS [3]. The Miller Capacitor C_X contributed to splitting the two poles and this effect improves stability and phase response. however, compromising bandwidth. Thus, Gate compensation is used to increase the bandwidth of the miller compensated amplifier. To do this Gate Resistor R_G is introduced between gate terminal and drain terminal of M3 and M8 [4]. Fig shows High Bandwidth Gate Compensated Transconductance Amplifier the is the modified version of Miller Compensated OTA. A new pole-zero pair is introduced due to the two Gate resistance R_G. Bandwidth is mainly dependent upon the dominant pole and with the help of R_G the introduced zero can be varied. Due to this phenomena, the dominant pole is now shifted away from the origin. And the overall bandwidth is now higher than the previous circuit.

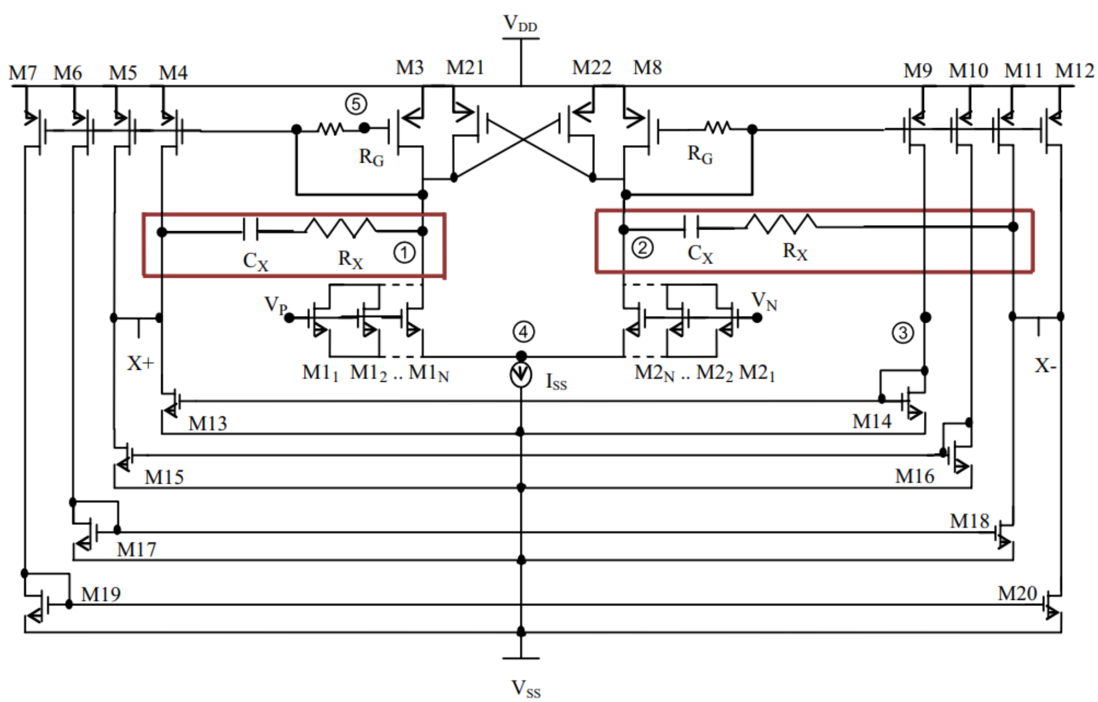

Fig.1 Gate Compensated High Bandwidth OTA [2]

Small signal analysis

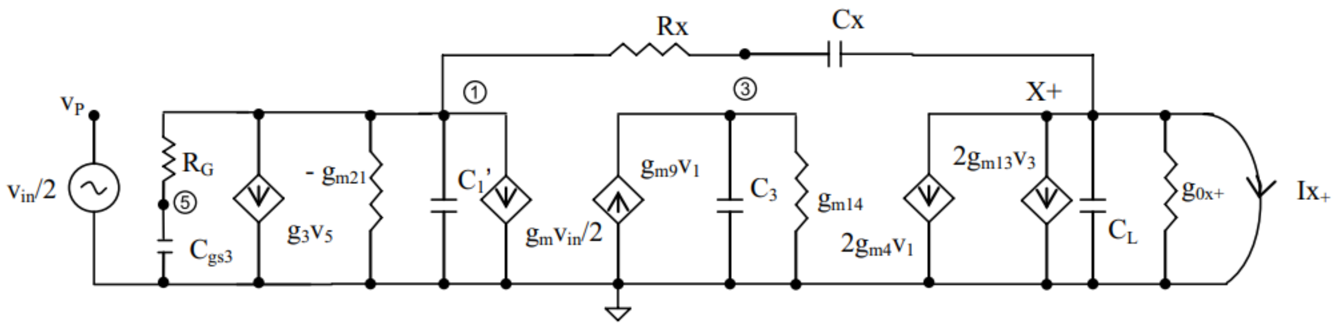

Fig.2 High frequency small signal model of Gate Compensated OTA [2]

Small signal equivalent circuit for the gate compensated OTA is shown in fig.2 and the values of the capacitances are mentioned below:

$C_1 = C_{ds1} + C_{ds3} + C_{ds21} + C_{gs3} + C_{gs4} + C_{gs5} + C_{gs6} + C_{gs7}$
$C_3 = C_{ds9} + C_{ds14} + C_{gs13} + C_{gs14}$
$C_L = C_L' + C_{ds4} + C_{ds5} + C_{ds13} + C_{ds15}$

Output conductance is given by:

$g_{0x+} = g_{04} + g_{05} + g_{013} + g_{015}$

To derive the current gain of the circuit, short the output node. Thus, the current gain in the form of transconductance is given by:

$$\frac{Ix}{Vin} = \frac{gm\,(\,sC3gm4 + gm4gm14 + gm9\,gm13)}{s2C1C3 + s\,\{\,C1gm14 + C3\,(\,gm3 - gm21)\} + gm14(\,gm3 - gm21)}$$

When C_X and R_X are added in Miller compensation;

$$I_X = -2gm_{13}vg_{13} - 2gm_4V_1$$

$$V3 = \frac{gm9}{sC3 + gm14}\;V1$$

$$V1 = \frac{gm}{(gm3 - gm21) + sC1 + sCX\,/(1 + sRXCX\,)}\,\frac{Vin}{2}$$

Thus, the current gain for Miller compensated OTA is now:

$$\frac{Ix}{Vin} = \frac{a2s2 + a1s + a0}{b3s3 + b2s2 + b1s + b0}$$

where,

$a_2 = C_3C_XR_Xg_mg_{m4}$
$a_1 = g_m\,(C_3g_{m4} + C_XR_Xg_{m4}g_{m14} + C_XR_Xg_{m9}g_{m13})$
$a_0 = g_{\,m}\,(g_{m4}g_{m14} + g_{m9}g_{m13})$
where, $b_3 = C_XR_XC_1C_3$
$b_2 = C_3\,(C_1 + C_X) + C_1C_XR_Xg_{m14} + C_XR_XC_3\,(g_{m3} - g_{m21})$
$b_1 = g_{m14}(C_1 + C_X) + C_XR_Xg_{m14}(g_{m3} - g_{m21}) + C_3\,(g_{m3} - g_{m21})$
$b_0 = g_{m14}(gm_3 - gm_{21})$

For a Gate compensated OTA;

$$I_X = -2gm_{13}vg_{13} - 2gm_4V_1$$

$$V3 = -\frac{gm9}{sC3 + gm14}\ V1$$

$$v1 - v5 = sCgs3RGv5$$

Thus, current gain obtained is:

$$\frac{Ix}{Vin} = \frac{c3s3 + c2s2 + c1s + c0}{d4s4 + d3s3 + d2s2 + d1s + d0}$$

where,

$c_3 = C_3C_{gs3}C_XR_XR_Gg_mg_{m4}$
$c_2 = g_m\,(C_3C_{gs3}R_Gg_{m4} + C_XR_X\,(C_3g_{m4} + C_{gs3}R_G\,(g_{m4}g_{m14} + g_{m9}g_{m13})))$
$c_1 = g_m\,(C_3gm_4 + C_{gs3}R_G\,(g_{m4}g_{m14} + g_{m9}g_{m13}) + C_XR_X\,(g_{m9}g_{m13} + g_{m4}g_{m14}))$
$c_0 = g_m\,(g_{m4}g_{m14} + g_{m9}g_{m13})$
$d_4 = C_XR_XC_1'C_3C_{gs3}R_G$
$d_3 = C_XR_X\,(C_1'C_3 + C_3C_{gs3} + C_{gs3}R_G\,(C_1'g_{m14} - C_3g_{m21})) + C_3C_{gs3}R_G\,(C_X + C_1')$
$d_2 = (C_1' + C_X)(C_3 + C_{gs3}g_{m14}R_G) + C_1'C_XR_Xg_{m14} + C_3C_XR_X(g_{m3} - g_{m21}) + C_{gs3}(C_3 + C_XR_Xg_{m14}) - C_{gs3}\,R_Gg_{m21}(C_3 + C_XR_Xg_{m14})$
$d_1 = (g_{m3} - g_{m21})(C_3 + C_XR_Xg_{m14}) + g_{m14}\,C_1' + g_{m14}\,C_X + g_{m14}\,C_{gs3}\,(1 - R_Gg_{m21})$
$d_0 = g_{m14}(g_{m3} - g_{m21})$

3. Gain Enhanced Telescopic OpAmp (Proposed OTA)

Gate compensated OTA improves the bandwidth of the Miller compensated circuit. Thus, these two compensation techniques help us improve the phase margin and bandwidth of the conventional OTA. The third metric that is Gain of the OTA can be enhanced using the Telescopic OpAmp topology. Telescopic OpAmp consists of an NMOS cascode stage at the bottom that is implemented to have a high impedance looking down the circuit. The circuit above is required to perform current mirror action with high impedance looking down the circuit as well. All the transistors except M1, M2 are self-biased, that is, the gate and drain terminals are connected to each other.

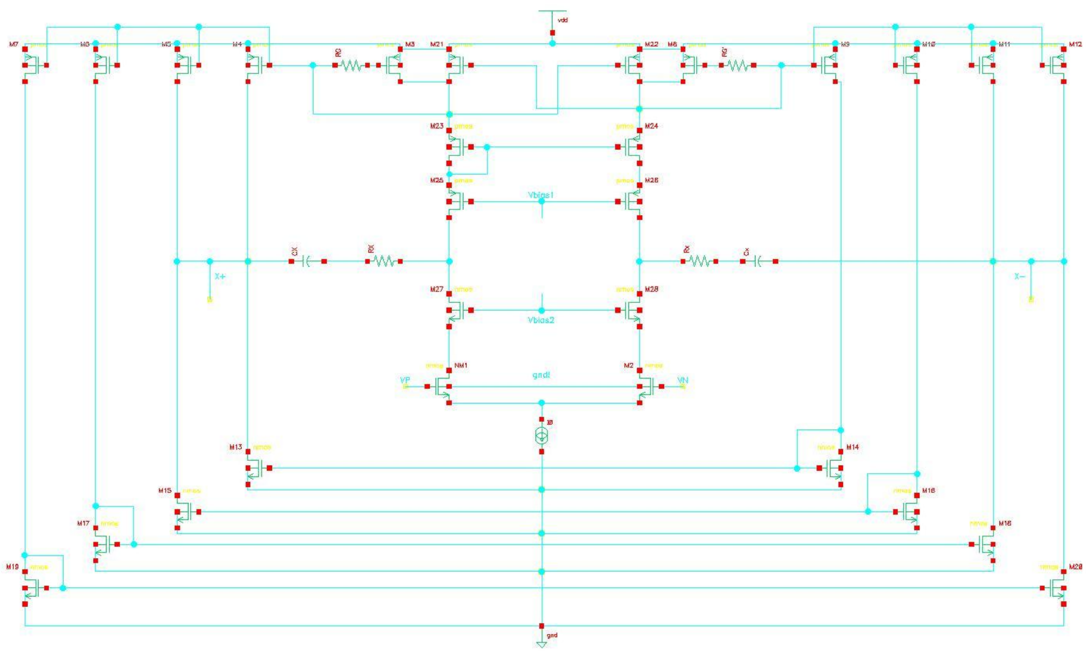

Fig.3 Gain Enhanced Gate compensated OTA using Telescopic OpAmp

4. Small Signal Analysis

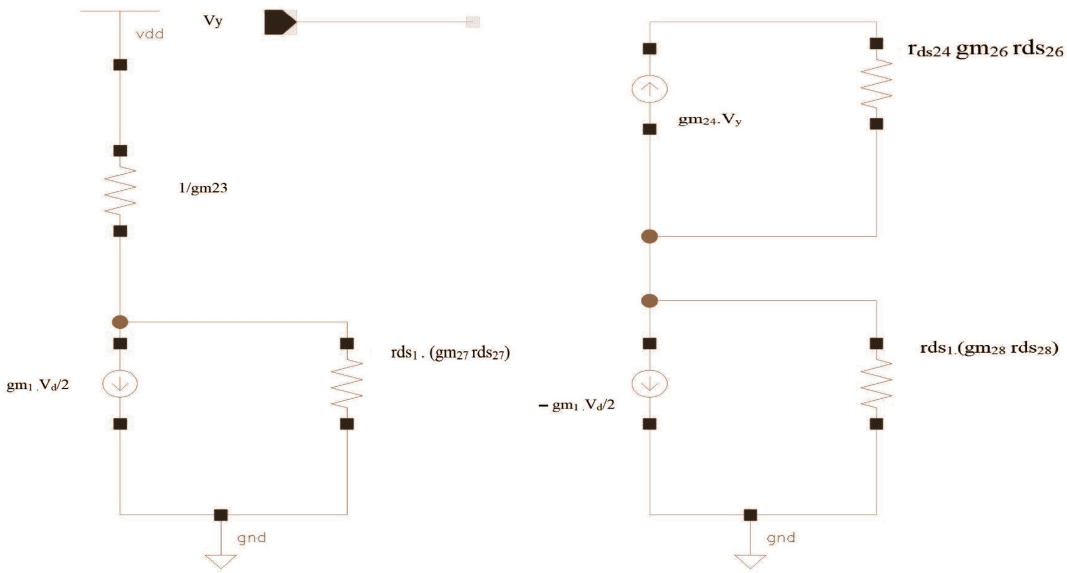

Fig.4 small signal model of Telescopic Opamp

I_X and V_X is given by:

$I_x = i_{d26} + i_{d28}$

$I_x = \frac{gm1vin}{2} + \frac{gm1vin}{2}$

$\therefore\ I_x = g_{m1}v_{in}$

$V_x = g_{m1}v_{in}R_2$

Thus, voltage gain is:-

$\frac{V_x}{V_{in}} = g_{m1}R_2$

R_2 is the equivalent resistance at the output node of the telescopic opamp;

$R_2 = \{(g_{m26}r_{ds26})r_{ds24}\} \mid\mid \{(g_{m28}r_{ds28})r_{ds2}\}$

The gain of the Telescopic opamp is approximately equal to the square of the gain of conventional OTA. As per the earlier study, gain of Gate compensated conventional OTA is:

$$g_{mgate} = \frac{Ix}{Vin} = \frac{c3s3 + c2s2 + c1s + c0}{d4s4 + d3s3 + d2s2 + d1s + d0}$$

where,

$c_3 = C_3C_{gs3}C_XR_XR_Gg_mg_{m4}$
$c_2 = g_m (C_3C_{gs3}R_Gg_{m4} + C_XR_X (C_3g_{m4} + C_{gs3}R_G (g_{m4}g_{m14} + g_{m9}g_{m13})))$
$c_1 = g_m (C_3gm_4 + C_{gs3}R_G (g_{m4}g_{m14} + g_{m9}g_{m13}) + C_XR_X (g_{m9}g_{m13} + g_{m4}g_{m14}))$
$c_0 = g_m (g_{m4}g_{m14} + g_{m9}g_{m13})$
$d_4 = C_XR_XC_1'C_3C_{gs3}R_G$
$d_3 = C_XR_X (C_1'C_3 + C_3C_{gs3}) + C_XR_XC_{gs3}R_G (C_1'g_{m14} - C_3g_{m21}) + C_3C_{gs3}R_G (C_X + C_1')$
$d_2 = (C_1' + C_X)(C_3 + C_{gs3}g_{m14}R_G) + C_1'C_XR_Xg_{m14} + C_3C_XR_X(g_{m3} - g_{m21}) + C_{gs3} C_3$
$(1 - R_Gg_{m21}) + C_XR_Xg_{m14}C_{gs3}C_3 (1 - R_Gg_{m21})$
$d_1 = (g_{m3} - g_{m21})(C_3 + C_XR_Xg_{m14}) + g_{m14}(C_1' + C_X) + C_{gs3} g_{m14}(1 - R_Gg_{m21}))$
$d_0 = g_{m14}(g_{m3} - g_{m21})$

Thus, gain of telescopic opamp can be approximated as:

$$g_m = \frac{I_x}{V_{in}} = (g_{mgate}r_{ds})^2$$

Other values in the equation remains same except that of C_1'

For an adaptively biased conventional OTA;
$C_1 = C_{ds1} + C_{ds3} + C_{ds21} + C_{gs3} + C_{gs4} + C_{gs5} + C_{gs6} + C_{gs7}$

When Gate compensation is applied;
$C_1' = C_1 - C_{gs3}$

When Telescopic opamp is implemented with the Gate compensated OTA;
$C_1'' = C_1' - C_{gs25}$

Gate compensated OTA gives us additional pole - zero pair compared to the conventional OTA i.e

$P_1 = \frac{-gm14}{C3}$

$P_{2,3,4}$ = *function of the* C_X, R_X, C_1, R_G, g_{m3}, g_{m21} *and* C_{gs3}

$Z_1 = \frac{-1}{Cgs3RG}$

$Z_2 = \frac{-1}{CXRX}$

$Z_3 = \frac{-gm4gm14 + gm9gm13}{C3gm4}$

Telescopic Opamp adds 6 poles out of which the pole due to the output node is the dominant pole;

$P_5 = f(C_X, R_X, C_1'', g_{m26})$

Among the non-dominant poles, the current mirror pole is the most significant one;

$P_6 = \frac{-gm23}{Cgs23}$

Following is the comparison for poles and zeroes in all 3 types of OTA - Conventional, Miller and Gate Compensated and Gain Enhanced Gate Compensated OTA

OTA Configurations	**No. of Poles**	**No. of zeroes**	**Bandwidth**	**Transconductance Gain (mA/V)**
Adaptively Biased OTA	2	1	16.10 MHz	9.2239
Miller Compensated OTA	3	2	5.73 MHz C_X=0.5 pF R_X=100 KΩ	9.2239
Gate Compensated OTA	4	3	33.31 MHz C_X=0.1 pF R_X=2 KΩ R_G=40 KΩ	9.2239
Gain Enhanced Gate Compensated OTA	6	5	30.39 MHz C_X=0.1 pF R_X=2 KΩ R_G=40 KΩ	18.5239

5. Design Parameters of Telescopic OpAmp for Gain Enhanced Gate Compensated OTA

The given Telescopic Opamp sizing is according to Conventional OTA sizing. The conventional OTA is operating at ±0.6 Volt supply voltage. Here for analysis supply voltage 1.8V is used. For DC analysis 100Ω resistance R_{OUT} is connected at output through which the graph between I_X and V_{IN} is obtained. A 100pF capacitor is also connected parallel with R_{OUT} resistance to measure the Transconductance gain and the voltage gain of the proposed circuit. It is found that the proposed circuit has increased gain by analyzing AC response.

For NMOS:

$$I_{DSAT} = \frac{\mu_N C_{OX} W \left(V_{GS} - V_{TH}\right)^2}{2L}$$

$$K_N^{'} = \mu_N C_{OX}$$

$$V_{DSAT} = V_{OV} = \left(V_{GS} - V_{TH}\right)^2$$

$$\frac{W}{L} = \frac{2I_{DSAT}}{K_N^{'} V_{OV}}$$

For PMOS:

$$I_{DSAT} = \frac{\mu_P C_{OX} W \left(V_{GS} - V_{TH}\right)^2}{2L}$$

$$K_P^{'} = \mu_P C_{OX}$$

$$V_{DSAT} = V_{OV} = \left(V_{GS} - V_{TH}\right)^2$$

$$\frac{W}{L} = \frac{2I_{DSAT}}{K_P^{'} V_{OV}}$$

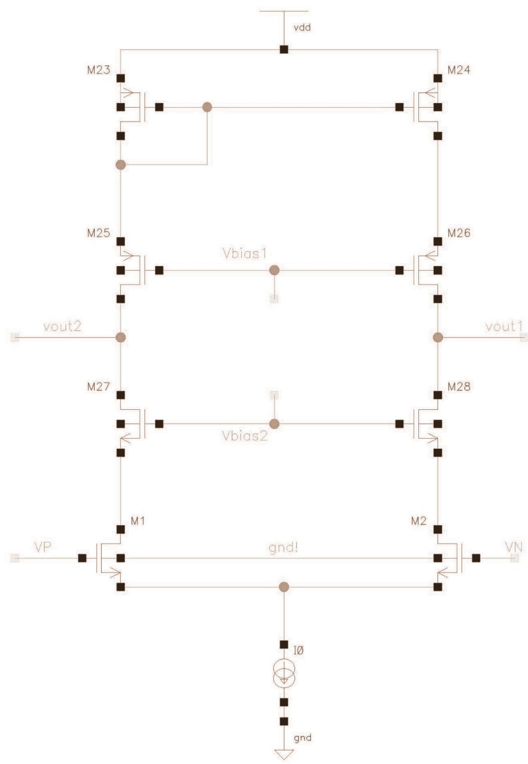

Fig. 5 Telescopic OpAmp Configuration

For UMC 0.18nm Technology

$K_N^{'}$ =300 uA/V^2

$K_P^{'}$ =60 uA/V^2

V_{thn0} = 487.5mV

V_{thp0} = -471.8mV

Table 1. Analysis for Gain Enhanced Gate Compensated OTA

For M_1 and M_2: $V_{g1} = V_{ds1} + V_{th1}$ $V_{g1} = 0.3 + 0.5$ $V_{g1} = 0.8$ V By characterization $W_{1,2} =$ 2 um **For M_{27} and M_{28}:** $V_{g27} = V_{ds27} + V_{ds27} + V_{th27}$ $V_{g27} = 0.3V + 0.3V + 0.5V$ $V_{g27} = 1.1V$ By characterization $W_{27\,,\,28} = 2.5$ um Vbias1 = 0.9V	**For M_{25} and M_{26}:** $V_{g25} = V_{s25} - V_{th25}$ $V_{g25} = 1.2V - 0.5V$ $V_{g25} = 0.7$ V By characterization $W_{25,26} = 8.5$ um **For M_{23} and M_{24}:** $V_{g23} = V_{ds23} - V_{th23}$ $V_{g23} = 1.5V - 0.5V$ $V_{g23} = 1.0$ V By characterization $W_{23,24} = 8.5$ um Vbias2=1.2V

Table 2. Parameters and their specifications used for Gate Compensated OTA

Parameters	**Specifications**
Technology	TSMC 0.18um
Supply voltage	$\pm$ 0. 6 Volts
Biasing Current	120uA
Temperature	27° C
Power Consumption	1.325mW
Aspect Ratios of MOSFETs 1. M1, M2 2. M3,M12 3. M13, M20 4. M21, M22	(W/L) 16u/1u 6.0u/1u 4.0u/1u 1.8u/0.35u

Table 3. Parameters and their specifications used for Telescopic OpAmp

Parameters	**Specifications**
Technology	UMC 0.18um
Supply voltage	1.8 Volts
Biasing Current	120uA
Temperature	27° C
Power consumption	571mW
Aspect Ratios of MOSFETs 1. M1, M2 2. M23,M24 3. M25, M26 4. M27, M28	(W/L) 2.0u/1u 8.5u/1u 8.5u/1u 2.5u/1u

6. Simulation Results

A. DC analysis of Gate Compensated OTA

After studying the Gate Compensated OTA the DC analysis is performed using Cadence Virtuoso 0.18um UMC technology. For this simulation one resistor Ro = 100 ohm is connected to output to get output current I_X with variation of V_{in} . while analyzing the result it is observed that the output curve is almost similar as compared to EldoSpice analysis. Current I_X is linearly varying within the range of -20mV to 20mV. In virtuoso specter the power consumption found is 1.325mW. This is due to increased power supply voltage.

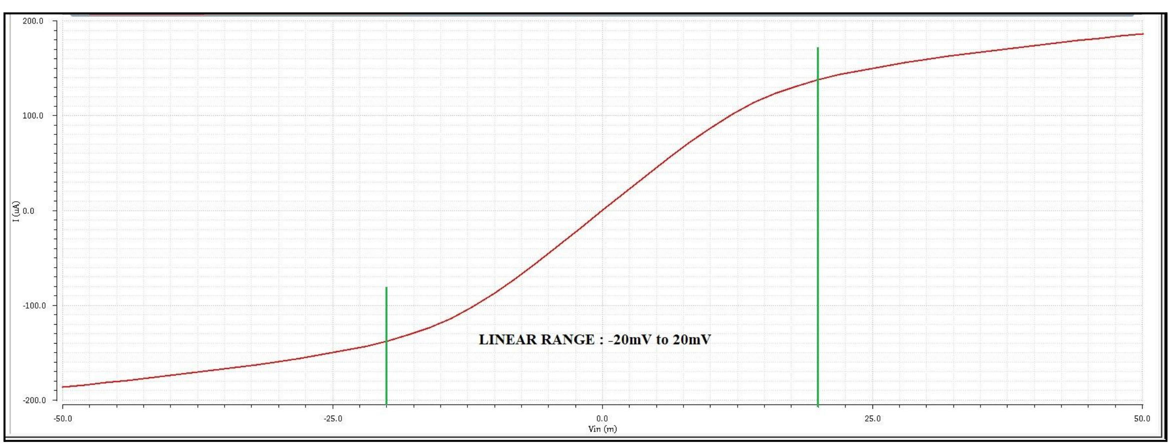

Fig. 6 DC response of Gate Compensated OTA

B. Analysis of Frequency Response of Gate Compensated OTA

For this analysis a Load Capacitor C_{Out} is used which has 100pF capacitance value . the voltage across this is carried for the analysis. The optimal value of obtained bandwidth is 33.313MHz with 51.40° phase margin for C_x =0.1pF and R_x = 2KΩ. This analysis also depicts that the small variation can occur while performing analysis on different technologies. Also by considering I_x across C_{out} and V_{in} the transconductance of the overall circuit is also obtained. Within the bandwidth the transconductance for the circuit is 9.22mA/V.

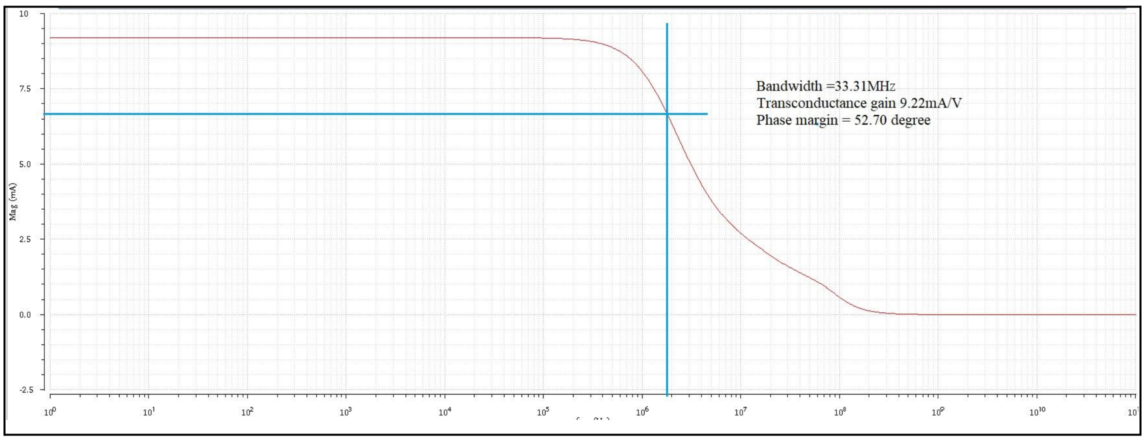

Fig. 7 Transconductance of Gate Compensated OTA

C. DC analysis of Gain Enhanced Gate Compensated OTA

In this analysis it is depicted that the output current I_x variation is almost doubled as compared to Gate compensated OTA. The linear variation range is als increased. And the overall power consumption is increased due to 4 more MOSFETs being introduced in the circuit. But in terms of high output current this can be preferable.

D. Frequency response

After AC analysis in Cadence Virtuoso it is inferred that the overall voltage gain is almost doubled as compared to Gate Compensated OTA. The earlier Voltage Gain of the differential amplifier was 100. That is now further increased to 912 due to telescopic topology. Also the bandwidth is somehow compromised within a small factor .

Table 4. Analysis Summary for Gate Compensated OTA

Parameters	Gate Compensated OTA
Power consumption	1.325mW
Linear Range	-20mV to 20mV
Bandwidth	33.31MHz
Phase Margin	51.40°
Transconductance	9.22mA/V

7. Conclusion

This paper presents OTA configuration that retains the benefits of the Miller and Gate Compensated OTA that is improved phase margin and bandwidth while improving the other significant performance metric which is gain of the OTA. Telescopic OpAmp topology introduced in the Gate compensated OTA enhances the gain provided proper characterization is achieved for the same. Even though there are other limitations involved when a telescopic topology is used such as limited output swing and high power consumption. However, it enhances the overall gain and stability of the OTA without affecting the phase margin and also bandwidth if the dominant pole value of the telescopic opamp is set higher than that by gate compensation.

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Availability of Data Material: It is not applicable

Conflict of Interest: It is declared that there are no differences of interest.

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